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TECHNICAL NOTE

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SATURN VEHICLE ATTITUDE RESOLVER

COMPUTER ERROR ANALYSIS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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TECHNICAL NOTE D-1119

SATURN VEHICLE ATTITUDE RESOLVER COMPUTER ERROR ANALYSIS

By Herman E. Thomason

SUMMARY

The results of a study to determine maximum RSS (root sum square) attitude error from the ST-124 inertial platform as used for the Saturn C-1 vehicle are presented. Each error has been discussed with possible improvements that could be made. The specification requirement of maximum error allowable is ± 6 arc minutes. The RSS analysis shows a maximum possible error of ± 3.15 arc minutes.

SECTION I. INTRODUCTION

The guidance, control, and navigation of a vehicle, such as the Saturn, in space require position and error deviation measurements to be within close tolerances. The ST-124 inertial platform has, fixed to each gimbal, pivot resolvers which are electrically connected in series with three program of command resolvers to form a resolver chain. The chain performs the coordinate transformation computations.[1] The output signals are furnished in form of angular error signals to the control computer for vehicle attitude correction; therefore, only angular errors contribute to system error. The Appendix is a summary of error study data with other important characteristics of chain operation. A photograph of the test setup used to obtain this data is included (Fig. 1).

SECTION II. DISCUSSION OF ERRORS

The ST-124 inertial platform and the program commands generate the vehicle attitude error signals from a resolver chain (Fig. 2)(Ref. 1). A resolver fitted to each gimbal pivot point resolves two orthogonal vectors about the third orthogonal axis. Trigonometric computations are performed by the resolvers which must be built with restrictive errors. For the ST-124 application (nulling system), angular errors are more

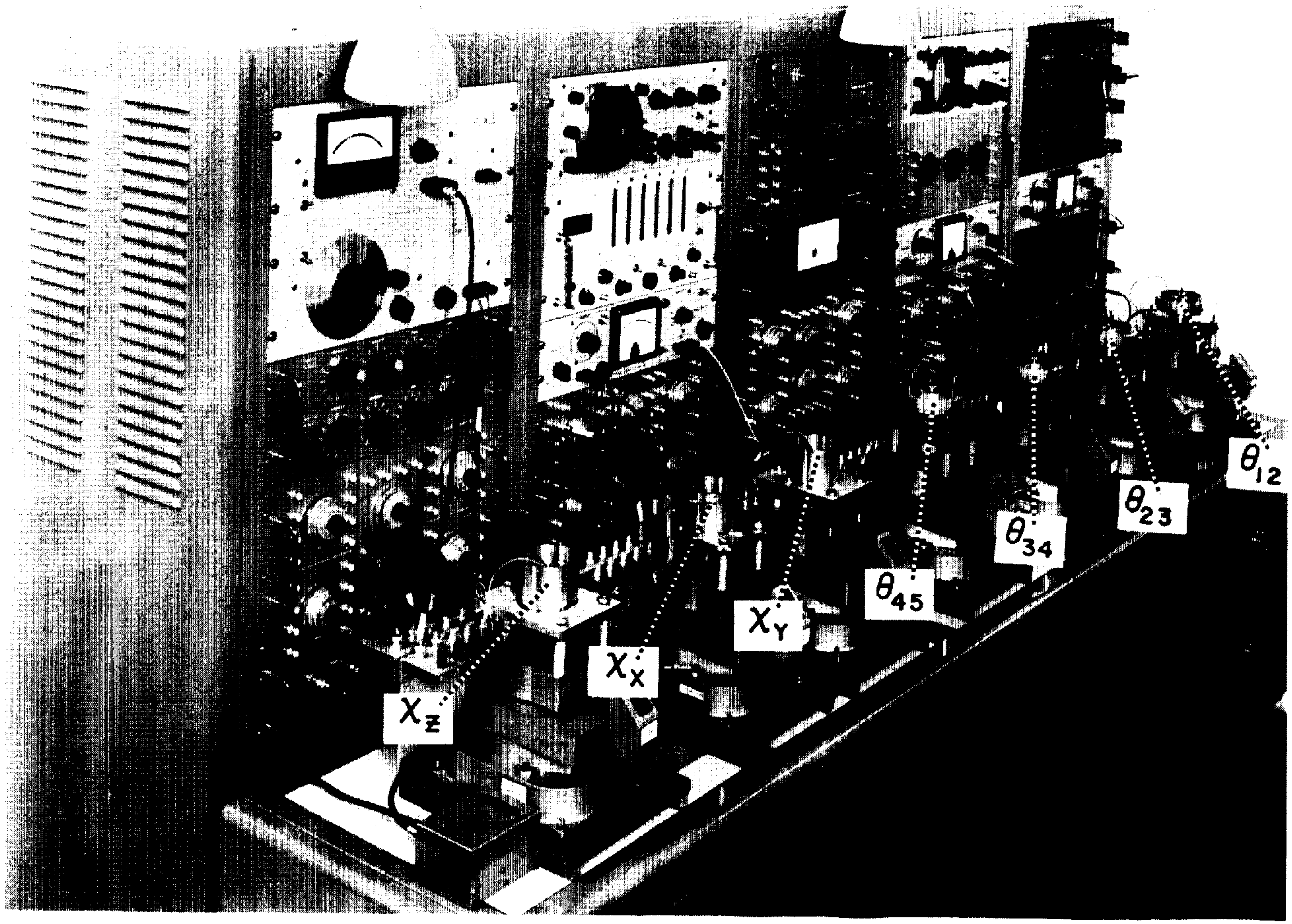


Figure 1. Test Setup

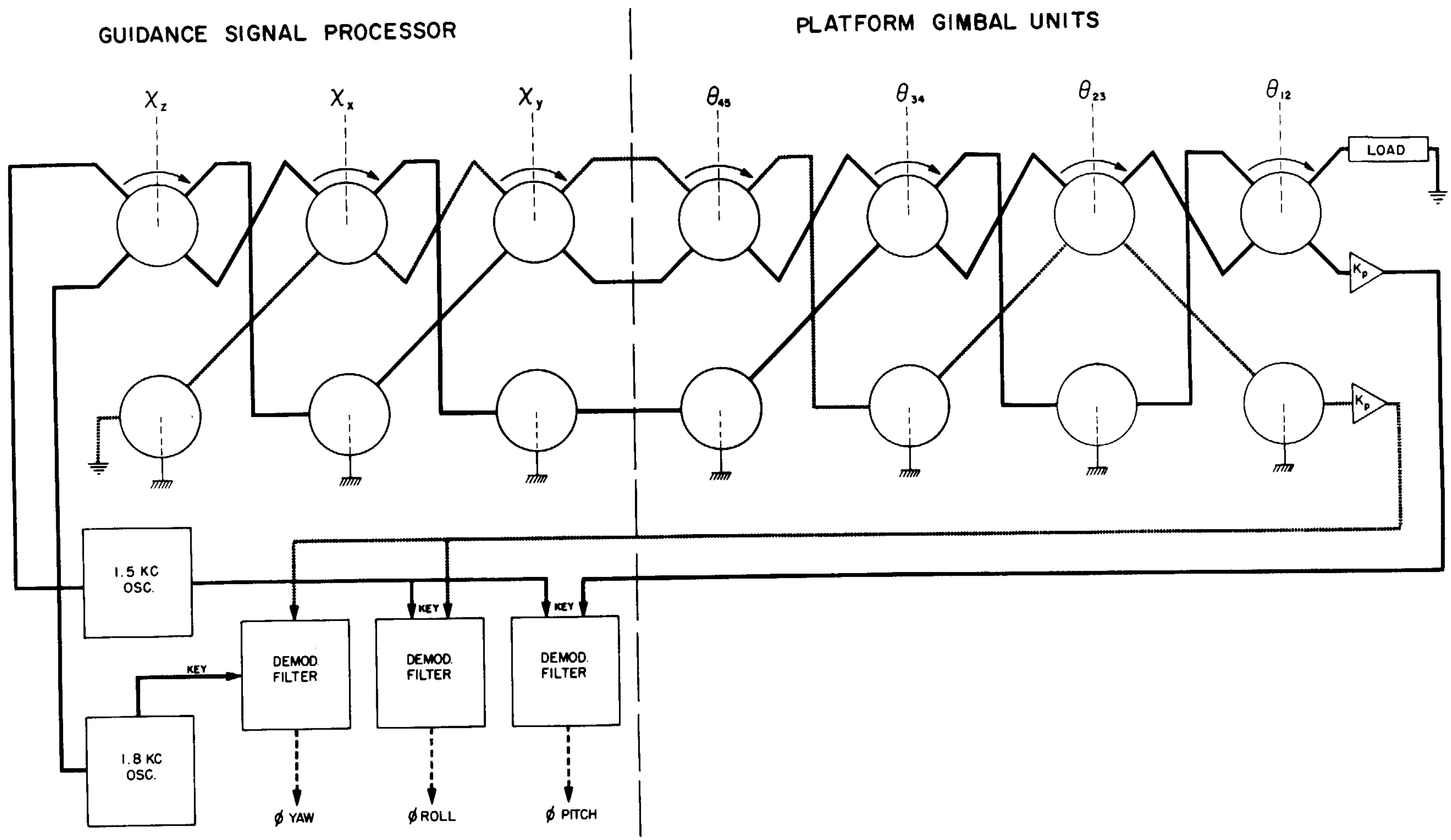


Figure 2. ST-124 Resolver Chain

important and contribute the majority of the system error. Functional errors, sine and cosine of an angle, can be held within extremely close limits of accuracy.

The ST-124 gimbals were designed for size 44 (greater than four-inch diameter) resolvers to provide a stacking lamination with a large number of winding slots (36 stator slots and 32 rotor slots). Thus a more sinusoidal flux distribution in the air gap is approached than with smaller units, which reduces the probability of detrimental slot harmonics. The resolver type of synchro design or a four-wire winding can be produced more readily for increased accuracy than the three wire winding. If the completed unit shows a slight winding unbalance, it can be corrected easier than Y-connected units. Another important factor is that high accuracy units require a definite ratio of lamination stack widths to diameters to insure electrical stability. The ST-124 units have a .5-inch stack thickness and a lamination size of 3.75-inch outside diameter with 1.457-inch rotor bore diameter.

Component Errors:

Resolver inaccuracies can be traced to many aspects in their construction. In general, all resolver errors are produced as a result of unbalances and dissymmetry of the magnetic flux path linking the primary to secondary windings. Specifically, the inherent errors can be separated into three distinct categories:

(1) perpendicularity and eccentricity errors
(2) functional errors
(3) transformation ratio unbalance errors.

The perpendicularity and eccentricity errors are a result of having two sets of windings which are not orthogonally located with respect to each other. Parameters which contribute to this are concentricity of rotor to stator, uniformity of the coils, coil distribution to the slots, and uniform thickness and orientation of the stack laminations.

Lack of concentricity causes deviations in the air gap length as the rotor is rotated. This error is manifested in the form of a two-cycle error when measured on a proportional voltage bridge. Flux density is varied for each angular rotor position, causing varying signal strengths to be transmitted. To control air gap variations, high precision integral race bearings limit axial movements; preloading eliminates radial play. Bearings are selected and precision fitted to the bore and rotor shaft.

The uniformity of the coils and distribution of the windings in the slots are calculated to the nearest sixth decimal place, and a harmonic analysis is made by computer facilities to determine the best round-off. This precaution minimizes stray magnetic effects and unbalance capacity between windings.

Lamination variations can only be controlled by strict quality control to assure uniform thickness and by indexing lamination stacks to equalize any die stamping deficiencies. Stacks are skewed to reduce the magnitude of slot errors. Slot harmonic errors appear as high frequency deviations superimposed on the basic angular accuracy curve. The fundamental frequency of the slot harmonics may be found from: 1/rotor slots - 1/stator slots = 1/cycles/revolution. The resolvers used on the ST-124 have 32 rotor slots and 36 stator slots, hence $\frac{1}{32} - \frac{1}{36} = \frac{1}{x}$; x = 18 cycles per revolution (fundamental). The magnitudes of the fundamental slot harmonic and its multiples (18, 36, 54, 72, etc.) are adjusted by the skew angle to give the least total error.

Functional errors, or the departure of the electrical outputs as a resolver from the ideal sine or cosine curve, are caused by slot spacing in the laminations which distort the magnetic field. Another cause for this deficiency lies in the number of coils available to reproduce a sinusoidal flux distribution in the unit (that is, the more slots and coils available, the closer the turn's distribution can approximate a true sine winding).

Transformation ratio unbalance is a result of unbalance between two sets of windings. The error is generated in a resolver because of dissimilar winding resistance and mechanical imperfections. The magnitude of this error varies with rotor shaft position and can be mininized by holding the maximum voltages equal in each phase. The most severe condition will exist at 45 degrees. Assuming unity electrical input to each phase, when a resolver is set to electrical zero, the shaft must be displaced 45 degrees to achieve a null condition. A one per cent unbalance in voltage input will cause a 17-minute error in shaft position. This can be demonstrated as follows.

(a) balanced inputs:

$$\theta = \tan^{-1} \frac{V_{R_{13}}}{V_{R_{24}}} = \tan^{-1} \frac{1}{1} = 45°$$

(b) 1% unbalance between inputs:

$$\theta + e = \tan^{-1} \frac{V_{R_{13}}}{V_{R_{24}}} = \tan^{-1} \frac{(1 + .01)}{1} = 45^\circ \quad 17''$$

Transformation ratio of the ST-124 resolvers is held to $1 \pm .02\%$. An additional advantage of a two-phase to two-phase resolver is that the input voltages are much easier balanced than a three-phase unit.

Temperature variations affect the performance characteristics of a resolver. Temperature causes a change in the value of winding resistance and inductance. These parameter variations result in a change in the transformation ratio and phase shift. The amplitude variations because of temperature change are usually a much smaller error than the phase shift change. The amplitude error is less than 0.075% for a temperature variation of -55° to +85°C. The resistance-temperature coefficient of copper is approximately 0.4% per degree centigrade and the phase shift varies proportionally. For example, a resolver operating at 20°C has a 1° phase shift for an ambient temperature variation of 10°C; an additional phase shift of .04° per degree centigrade change is experienced or a .4% phase shift change per degree centigrade ambient variation. The major contributor to this error is the copper resistance change. The first ST-124 systems being built will depend on close temperature control; an investigation to add a thermistor to the resolver circuit for future systems is being evaluated. Other means will also be considered, such as employing a compensator winding in conjunction with a high gain amplifier.

Additional errors to be considered are those resulting from frequency and excitation voltage variations. Even when operating under the most ideal conditions, resolvers generate some harmonics in the output because of the non-linear characteristics of magnetic materials. The harmonic content of the output is greatly increased if the resolver is operated in any condition of core saturation. The use of the highest quality magnetic materials and accurate design minimize these variations.

Chain Errors:

The Discussions have been limited to single components; cascaded resolvers have inherent errors in addition to the basic component inaccuracies. Special care must be taken to assure a balanced impedance load and identical tracking of the resolver with its matched dummy. Because copper resistance and inductance change with temperature, it is advantageous to keep the matched set of resolver and dummy in the same enviromental temperature. The ST-124 inertial platform resolvers have a specified inherent unit error of 20 seconds. For these resolvers, a change in transformation ratio of .005% to .008% per degree centigrade is typical. A differential temperature of 5°C between unit and dummy will cause a transformation ratio unbalance error of approximately .025%.

The general expression for angular error caused by impedance unbalance can be expressed mathematically as follows.

$$\Delta\theta = \frac{\Delta Z(Z_{so}Z_{rs}) \sin 2\theta}{2Z_L(Z_{so}Z_{rs} + Z_{ro}Z_L)}$$

where

ΔZ = impedance load unbalance

Z_{so} = stator impedance with rotor open circuited

Z_L = load impedance

Z_{rs} = rotor impedance with stator short circuited

Z_{ro} = rotor impedance stator open circuit

From this expression, impedance mismatch can be identified as two-cycle in nature. This error can be minimized by maintaining the load impedance as high as possible while decreasing the rotor impedance with stator short circuited. For this reason, a large impedance ratio (minimum of 10) of Z_L/Z_{rs} was made between cascaded units in the chain.

Resolver component's errors are classed either random or constant; but in the cascaded chain, the errors are random in both magnitude and phase relation. Therefore, an RSS type error analysis based on maximum component errors will be used for predicting the system accuracy. Statistically, the chances for all errors to be at maximum value and added are highly improbable. This analysis of errors based on the RSS method of maximum error is pessimistic in nature and results in the worst possible error.

Considering the error factors discussed, the system error for the seven cascaded resolver units of the ST-124 inertial platform will be analyzed. All data are furnished in the Appendix.

A. Component Angular Error

1. Ideal RMS output voltage = transformation ratio (RMS excitation) x sin of displacement angle

Error = 20 arc seconds per unit (maximum)

Chain RSS = $20\sqrt{7}$

= 52.8 seconds.

2. Functional error = $\sqrt{(\text{component angular error})^2 + (\text{quadrature voltage})^2}$

Quadrature voltage ≈ .008% of excitation (26 volts)

= $\sqrt{(.057\%)^2 + (.168\%)^2}$

= .177%

B. Transformation ratio errors must be analyzed as roll, pitch, and yaw errors, separately. Thus the effect of a command generated by the program resolvers (χ_Z) and nulling the chain by rotation of the gimbal resolvers (θ_{12}) (completion of vehicle control loop) would be the largest error. Transformation ratio of resolvers is matched to .02%; transformation ratio between resolver and dummy is matched to .1%. This variation would be random; therefore, an RSS analysis must be used. Referring to Figure 3, Table 1 is constructed.

Table 1
TRANSFORMATION ERRORS

Component	* Pitch (%)	* Roll (%)	* Yaw (%)
χ_Z	.02	0	0
χ_X	.02	0	.02
χ_Y	.1	.02	.02
θ_{45}	.1	.02	.02
θ_{34}	.02	0	.1
θ_{23}	.02	0	.02
θ_{12}	.02	0	0
Sum squared	.0220	.0008	.0116
RSS	.148	.0282	.1074

* Pitch, roll, and yaw as designated from the platform initial position in the vehicle.

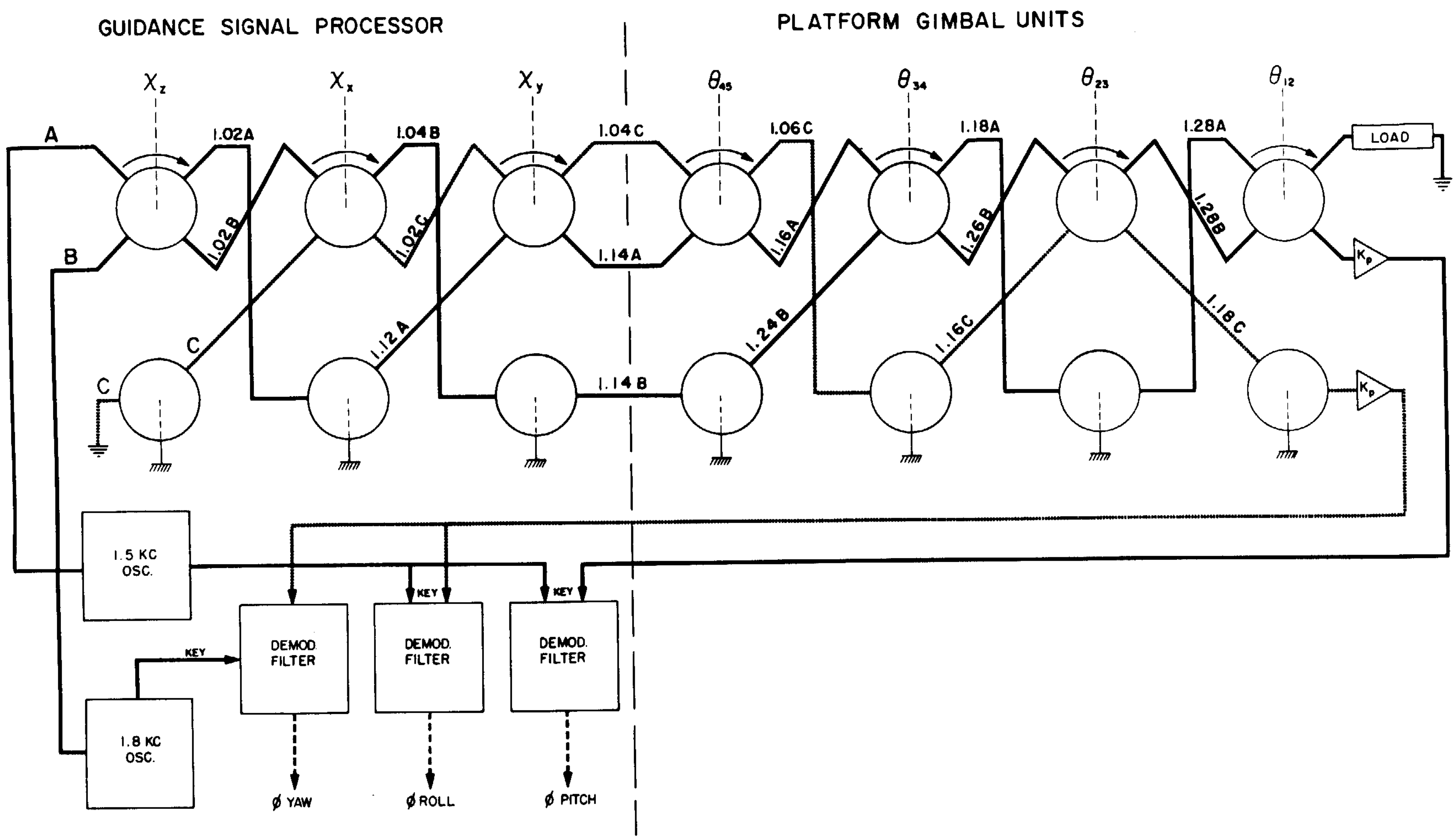


Figure 3. ST-124 Resolver Chain, Transformation Ratio Variation Summed Through Chain

The maximum error generated will exist with a component shaft angle of 45 degrees.

1. Pitch error

   $$\theta + e = \tan^{-1} \frac{(1 + .00148)}{1} = \tan^{-1} 1.00148$$

   $$\theta + e = 45^\circ \ 2.28'$$

   an error of 2.28 arc minutes.

2. Roll error

   $$\theta + e = \tan^{-1} \frac{(1 + .000282)}{1} = \tan^{-1} 1.000282$$

   $$\theta + e = 45^\circ \ 0' \ 28.7''$$

   an error of 28.7 arc seconds.

3. Yaw error

   $$\theta + e = \tan^{-1} \frac{(1 + .001074)}{1} = \tan^{-1} 1.001074$$

   $$\theta + e = 45^\circ \ 1.84'$$

   an error of 1.84 arc minute.

4. Maximum functional error = .148%.

C. Scale factor change because of change in temperature (functional error only):

1. Based on ±25°C change in guidance signal processor.

   $$\frac{.008\%}{^\circ C} \times 25 = .2\% \text{ per unit} \times 3 = .6\%.$$

2. Based on ±10°C average change in platform

   $$\frac{.008\%}{^\circ C} \times 10 = .08\% \text{ per unit} \times 4 = .32\%$$

   Total - (1 + 2) = .92%.

D. Changes in chain output as a result of varying excitation voltages and frequency are due to the B-H-curve non-linearity of the magnetic materials and a shift in hysteresis loop areas. Through the ST-124 chain, four conditions of excitation voltage or flux density exist.

Condition 1: Constant RMS voltage, constant frequency components applied to the excitation windings

Condition 2: Constant RMS voltage, varying frequency components

Condition 3: Varying RMS voltage, varying frequency, total flux varies from 50% to 100% at maximum

Condition 4: Varying RMS voltage, varying frequency, total flux varies from 0% to 100% at maximum

The resolver chain for the ST-124 with the component flux density distribution for varying conditions noted is shown in Figure 4. The flux condition shown is for operating conditions with small (less than 10°) error signals.

The angular error for worst possible conditions is (refer to normalized curves A-1, A-2, A-3, and A-4 for per cent variation in transformation ratio):

1. Yaw error

$$\theta + e = \tan^{-1} \frac{(.999)(.999)(.994)}{(.999)(.994)(.994)}$$

$$\theta + e = \tan^{-1} 1.005$$

$$\theta + e = 45° \quad 8.5'$$

an error of 8.5 arc minutes.

2. Pitch error

$$\theta + e = \tan^{-1} \frac{(.999)(.999)(.999)(.994)(.999)}{(.999)(.994)(.994)(.999)(.999)}$$

$$\theta + e = \tan^{-1} 1.005$$

$$\theta + e = 45° \quad 8.5'$$

an error of 8.5 arc minutes.

3. Roll error = 0.

To reduce this error, a third reference frequency imposed on the Z-channel will result in all resolvers operating in condition 1 or condition 2. An alternate method would be to excite the second winding on each dummy which will eliminate condition 4. This method has

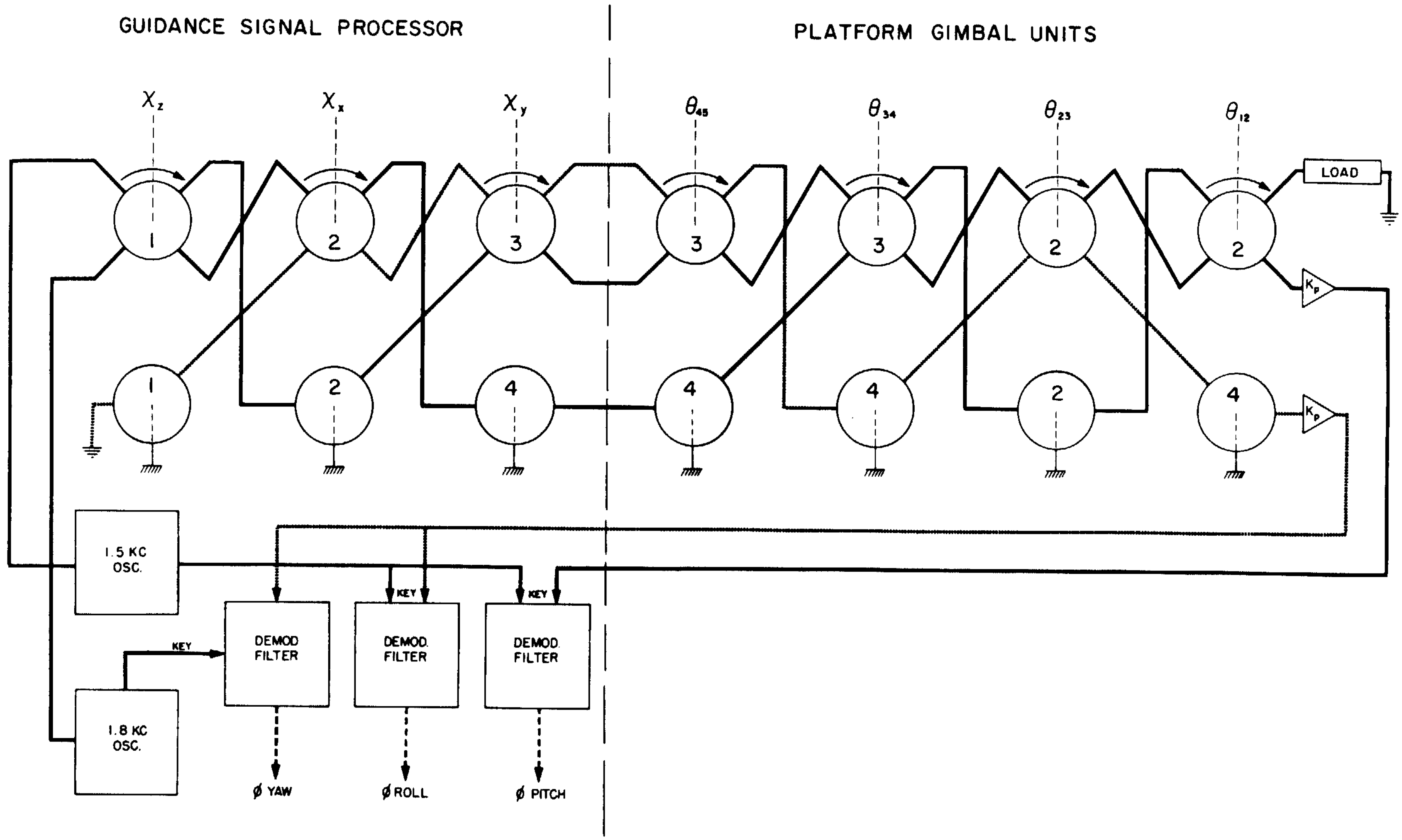


Figure 4. ST-124 Resolver Chain, Units Flux Density Condition

been chosen for the ST-124 (Fig. 5). Secondary advantages gained are that f_2 (1.8KC) can be used to reduce the filtering problems as f_2 (1.8KC) is available in proper magnitude and phase relation at output of chain to cancel the unwanted frequency on the pitch channel.

The angular error generated with these conditions and 45 degree shaft position is again computed.

1. Yaw error

$$\theta + e = \tan^{-1} \frac{(1)(1)(.999)}{(1)(.999)(.999)}$$

$$\theta + e = \tan^{-1} \ 1.001$$

$$\theta + e = 45^\circ \quad 1.71'$$

an error of 1.71 arc minutes = 102.6 arc seconds.

2. Roll error = 0.

3. Pitch error

$$\theta + e = \tan^{-1} \frac{(1)(1)(1)(.999)(1)}{(1)(.999)(.999)(1)(1)}$$

$$\theta + e = \tan^{-1} \ 1.001$$

$$\theta + e = 45^\circ \quad 1.71'$$

an error of 1.71 arc minutes = 102.6 arc seconds.

4. Functional error $= 102.6 \times \dfrac{.1\%}{1.7 \times 60} = .106\%$

E. Loading errors because of unbalance impedance is attributed to each resolver secondary winding looking into a different (but constant) impedance. As the resolver shaft rotates, different loads are seen by the primary. Angular error is expressed by equation:

$$\Delta_\theta = \frac{\Delta Z(Z_{so} \times Z_{rs}) \sin 2\theta}{2Z_L(Z_{so} Z_{rs} + Z_{ro} Z_L)}$$

Table 2 shows error contributions from each component. See the Appendix for test data used in computing these deviations. $\Delta Z = 3\%$ as determined by the resolver manufacturer.

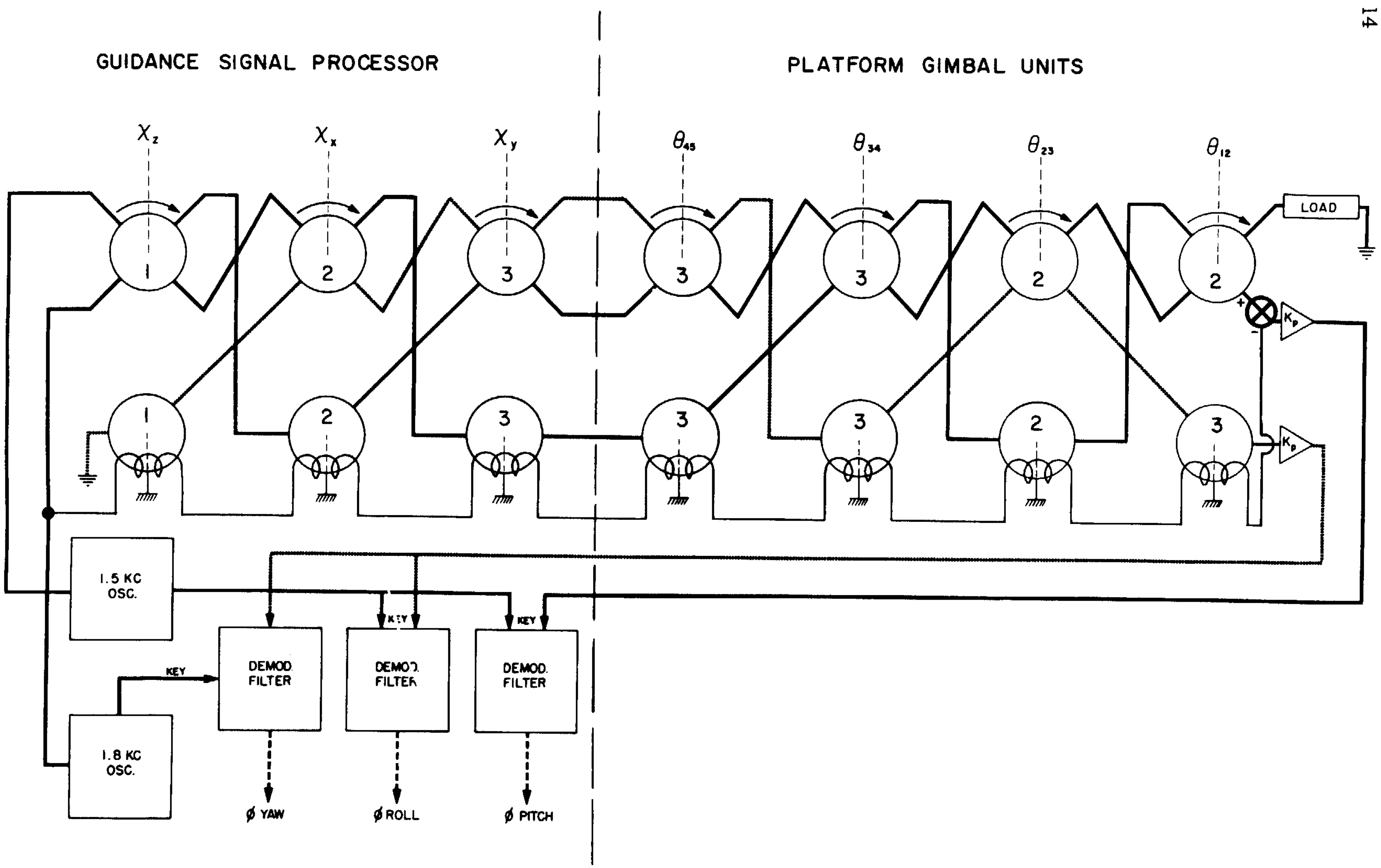


Figure 5. ST-124 Resolver Chain, Units Flux Density Condition

Table 2
ERROR BECAUSE OF UNBALANCE LOAD IMPEDANCE

Component	Error (arc seconds)	$(\text{error})^2$
X_Z	14.1	198
X_X	17.3	302
X_Y	25.1	633
θ_{45}	66.3	440
θ_{34}	92	845
θ_{23}	2.7	7.3
θ_{12}	17.55	310
	Total sum squared	2735.3

1. Therefore, total RSS error for maximum error condition will be 52 arc seconds.

2. Functional error $= 52 \times \frac{.1\%}{(17)(6)} = .05\%$

F. Chain errors because of unbalance impedance and transformation ratio changes resulting from ambient temperature variations.

These errors are a result of temperature variations between the active resolver and the impedance matching dummy. If the two units are subjected to the same environment and the dummy is an exact impedance equivalent of the active unit, each signal path is subjected to identical conditions. An equal attenuation and phase shift of the signal will result. The amplitude error is less than .075% for a temperature variation of $-55°$ to $+85°$ C. The resistence temperature coefficient of copper is approximately 0.4% per degree centigrade; the phase shift varies in a like manner. For a 25°C temperature variation in a chain that has a 10° phase shift, the phase shift change is approximately $(.004)(25)(10) = 1°$. The result is a change in the error gradient (phase and quadrature) at the null of the chain output and not an angular error.

Angular errors are generated when temperature variations between the active resolver unit and the matching dummy units are not equivalent.

The active unit and dummy use identical laminations and windings; close quality control is exercised in the manufacture to insure matched conditions. Units are matched to exact impedances with trimming resistors.

Tests have been made for a ±10° C change in all platform units with command units held constant and a ±25° C change in all command units with all platform units held constant.

Results of these tests show a maximum error of .01% per degree centigrade temperature change between the active unit and the dummy. Initial chains are being assembled with three program units packaged with the matching dummy. The final platform system will have the dummies and active resolvers packaged together and mounted to proper pivot; therefore, any possibility of temperature variation in any unit greater than 1°C to 2° C will be eliminated. First platform systems will separate the active unit from the dummies because of space requirements.

Considering the worst possible condition of a 45 degree pivot angle existing and a 10° C variation between active resolver and dummy unit, the following errors exist:

$$\text{Pivot}_{45}\ \text{error} = 45^\circ - \tan^{-1} \frac{.87790}{.87777}$$

$$\text{error} = 45^\circ - \tan^{-1} 1.00014$$

$$\text{error} = 13.6 \text{ arc seconds}$$

$$\text{Pivot}_{34}\ \text{error} = 45^\circ - \tan^{-1} \frac{.84743}{.84728}$$

$$\text{error} = 45^\circ \tan^{-1} 1.00017$$

$$\text{error} = 16.5 \text{ arc seconds}$$

$$\text{Pivot}_{23}\ \text{error} = 45^\circ \tan^{-1} \frac{80581}{80560}$$

$$\text{error} = 45^\circ \tan^{-1} 1.00026$$

$$\text{error} = 25.3 \text{ arc seconds}$$

1. RSS angular error $= \sqrt{(13.6)^2 + (16.5)^2 + (25.3)^2}$

$= \sqrt{1099.2}$

Total RSS error = 33.1 arc seconds.

2. Functional error $= 33.1 \times \frac{.1\%}{(1.7)(60)} = .0325\%$.

G. 1. The total angular chain RSS error can be computed:

RSS system angular error (arc seconds)
$$= \sqrt{(A)^2 + (B)^2 + (D)^2 + (E)^2 + (F)^2}$$
$$= \sqrt{(52.8)^2 + (136.8)^2 + (102.6)^2 + (52)^2 + (33.1)^2}$$
$$= 189 \text{ arc seconds}$$
$$= 3.15 \text{ arc minutes}$$

2. Total functional chain RSS error can also be computed:

RSS functional error
$$= \sqrt{(A)^2 + (B)^2 + (C)^2 + (D)^2 + (E)^2 + (F)^2}\,\%$$
$$= \sqrt{(.177)^2 + (.148)^2 + (.92)^2 + (.106)^2 + (.05)^2 + (.0325)^2}\,\%$$
$$= \sqrt{.914525}\,\%$$
$$= .956\%$$

SECTION III. CONCLUSION

The design goal of six arc minutes has been met with a safe margin. Each error contribution has been computed with worst possible conditions and errors will be updated as additional test data become available. The use of a dual frequency chain has been test proven. Computation for varying excitation and flux disturbance errors shows that a reduction of the major portion of the greatest error is realized by the use of two frequency references. Additional advantages will also be realized by choosing locations for active resolver units and dummies on gimbal points. Phasing through the chain is controlled by tuning at 1750 cps; tests show chain phase shift to be 9° which can be reduced by closer impedance matching at operating frequency at each point in the chain.

The ST-124 resolver chain operates in a nulling mode for all operations, thus reducing any importance of the functional error. If a requirement necessitates a reduction of this error, a closer control of temperature variations of the resolvers ambient temperature must be held.

REFERENCE

1. NASA TN D-1118, Herman Thomason and R. L. Moore, Gimbal Geometry and Attitude Sensing of the ST-124 Stabilized Platform, May 1962.

APPENDIX

Table A-1

CHAIN DATA SUMMARY

Transformation Ratio (Eo/Ein)	.8318
Phase Shift	9°
Sensitivity (volt/degree)	0.250
Total Nulls (maximum)	20 MV
Input Power (watts/channel)	.79
Angular Accuracy (minutes)	±3.15
Functional Error (maximum)	.956%

Table A-2

SUMMARY OF DATA FOR TRANSFORMATION RATIO VARIATIONS
WITH VARYING AMBIENT TEMPERATURES

Transformation Ratio and Phase Shift

Ambient Condition	Resolver Subjected to 10° C Change		χ_Z	χ_X	χ_Y	θ_{45}	θ_{34}	θ_{23}	θ_{12}	Total Chain
1	none	TR	.86311	.90051	.93657	.80581	.84743	.87790	1.26000	.54985
		θ	-1.0054°	-1.0796°	-1.3262°	4.8821°	2.7104°	3.4712°	1.5000°	9.1526°
2	θ_{12}	TR	.86311	.90051	.93657	.80583	.84745	.87794	1.26000	.54990
		θ	-1.0054°	-1.0793°	-1.3259°	4.8799°	2.7053°	3.4575°	1.5001°	9.1322°
2	θ_{23}	TR	.86311	.90051	.93657	.80584	.84747	.8777	1.26000	.54982
		θ	-1.0056°	-1.0796°	-1.3264°	4.8767°	2.6982°	3.4961°	1.5000°	9.1594°
2	θ_{34}	TR	.86311	.90052	.93659	.80585	.84728	.87790	1.26000	.54979
		θ	-1.0056°	-1.0798°	-1.3271°	4.8685°	2.7358°	3.4712°	1.5000°	9.1630°
2	θ_{45}	TR	.86311	.90053	.93662	.80560	.84743	.87790	1.26000	.54975
		θ	-1.0063°	-1.0811°	-1.3306°	4.9230°	2.7104°	3.4712°	1.5000°	9.1866°
2	χ_Y	TR	.86311	.90052	.93656	.80581	.84743	.87790	1.26000	.54985
		θ	-1.0061°	-1.0806°	-1.3252°	4.8821°	2.7104°	3.4712°	1.5000°	9.1519°
2	χ_X	TR	.86312	.90050	.93657	.80581	.84743	.87790	1.26000	.54985
		θ	-1.0073°	-1.0776°	-1.3262°	4.8821°	2.7104°	3.4712°	1.5000°	9.1526°
2	χ_Z	TR	.86309	.90051	.93657	.80581	.84743	.87790	1.26000	.54984
		θ	-1.0029°	-1.0796°	-1.3262°	4.8821°	2.7104°	3.4712°	1.5000°	9.1550°
3	θ_{12} θ_{23} θ_{34} θ_{45}	TR	.86315	.90062	.93687	.80352	.84589	.87618	1.25900	.54605
		θ	-1.0088°	-1.0867°	-1.3442°	5.1538°	2.9055°	3.6517°	1.6022°	9.9134°

Table A-3

COMPONENT ELECTRICAL PARAMETERS

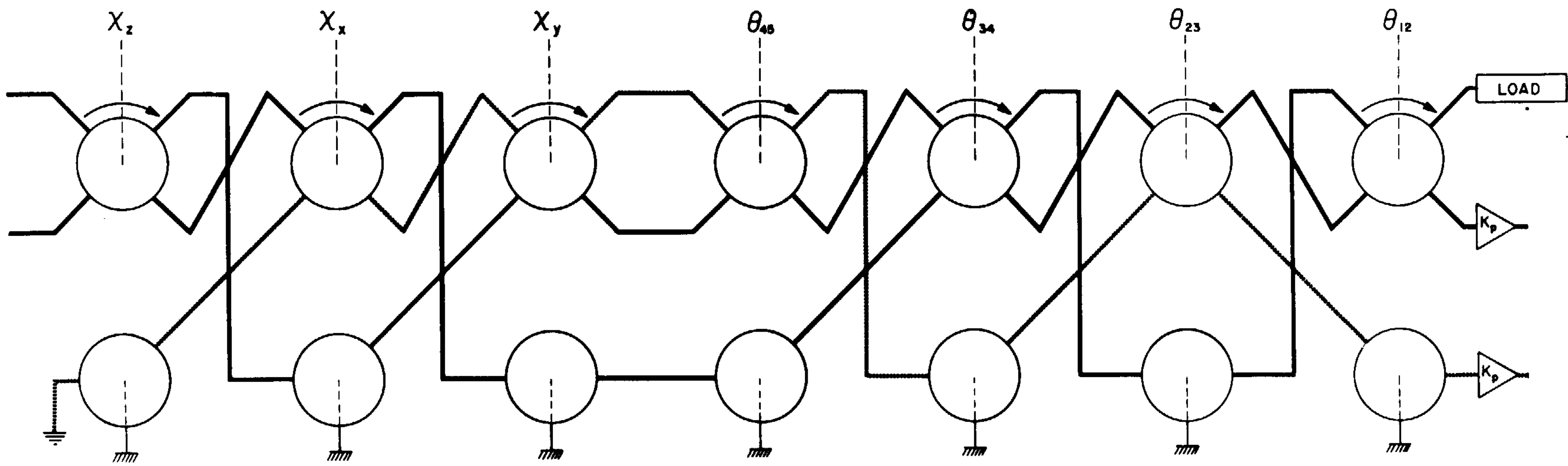
Resolver Component	Electrical Characteristics
χ_Z	Primary - Rotor $Z_{ro} = 100.3 + j351.6$ $Z_{so} = 117.7 + j412.7$ $Z_{ss} = 63.6 \angle 77.3^{\circ}$ ohms $Z_{rs} = 54.4 \angle 77.3^{\circ}$ ohms TR = 1 Phase Shift = 0.32°
χ_X	Primary - Stator $Z_{ro} = 179.7 + j603.5$ $Z_{so} = 210.8 + j708.7$ $Z_{ss} = 106 \angle 78.1^{\circ}$ ohms $Z_{rs} = 90.1 \angle 78.1^{\circ}$ ohms TR = 1 Phase Shift = -0.35°
χ_Y	Primary - Stator $Z_{ro} = 402.9 + j1293.5$ $Z_{so} = 473 + j1519.6$ $Z_{ss} = 238 \angle 77.1^{\circ}$ ohms $Z_{rs} = 203 \angle 77.1^{\circ}$ ohms TR = 1 Phase Shift = -0.36°
θ_{45}	Primary - Stator $Z_{ro} = 2575 + j5750$ $Z_{so} = 3196 + j6990$ $Z_{ss} = 1473 \angle 47.3^{\circ}$ ohms $Z_{rs} = 1210 \angle 48.8^{\circ}$ ohms TR = 1 Phase Shift = +1.75°

Table A-3 (Cont'd)

Resolver Component	Electrical Characteristics
θ_{34}	Primary - Rotor $Z_{ro} = 3974 + j9140$ $Z_{so} = 4906 + j11,100$ $Z_{ss} = 2220 \angle 53.8°$ ohms $Z_{rs} = 1825 \angle 54.2°$ ohms TR = 1 Phase Shift = 1.15°
θ_{23}	Primary - Stator $Z_{ro} = 7660 + j17,350$ $Z_{so} = 9500 + j21,050$ $Z_{ss} = 4340 \angle 50.6°$ ohms $Z_{rs} = 3560 \angle 51.0°$ ohms TR = 1 Phase Shift = 1.5°
θ_{12}	Primary - Stator $Z_{ro} = 12,160 + j27,450$ $Z_{so} = 23,800 + j52,700$ $Z_{ss} = 10750 \angle 49.7°$ ohms $Z_{rs} = 5670 \angle 50.2°$ ohms TR = 1.26 Phase Shift = 1.5°

Table A-4

RESOLVER COMPUTER ELECTRICAL PARAMETER



1. Input impedance at $X_Z = 204$ $\angle 74^\circ$ ohms
2. Output impedance at $X_Z = 63.7$ $\angle 77.8^\circ$ ohms
3. Input impedance at $X_X = 400$ $\angle 72.9^\circ$ ohms
4. Output impedance at $X_X = 167.8$ $\angle 77.2^\circ$ ohms
5. Input impedance at $X_Y = 988.7$ $\angle 70.2^\circ$ ohms
6. Output impedance at $X_Y = 386.9$ $\angle 76.6^\circ$ ohms
7. Input impedance at $\theta_{34} = 3395.4$ $\angle 61.9^\circ$ ohms
8. Output impedance at $\theta_{45} = 1788$ $\angle 54.3^\circ$ ohms
9. Input impedance at $\theta_{34} = 5{,}899$ $\angle 64^\circ$ ohms
10. Output impedance at $\theta_{34} = 12{,}211$ $\angle 64.3^\circ$ ohms
11. Input impedance at $\theta_{23} = 12{,}211$ $\angle 64.3^\circ$ ohms
12. Output impedance at $\theta_{23} = 7{,}424$ $\angle 54.6^\circ$ ohms
13. Input impedance at $\theta_{12} = 30{,}023$ $\angle 66^\circ$ ohms
14. Output impedance at $\theta_{12} = 20{,}039$ $\angle 54.8^\circ$ ohms
15. Load impedance $\geq 180{,}000$ ohms

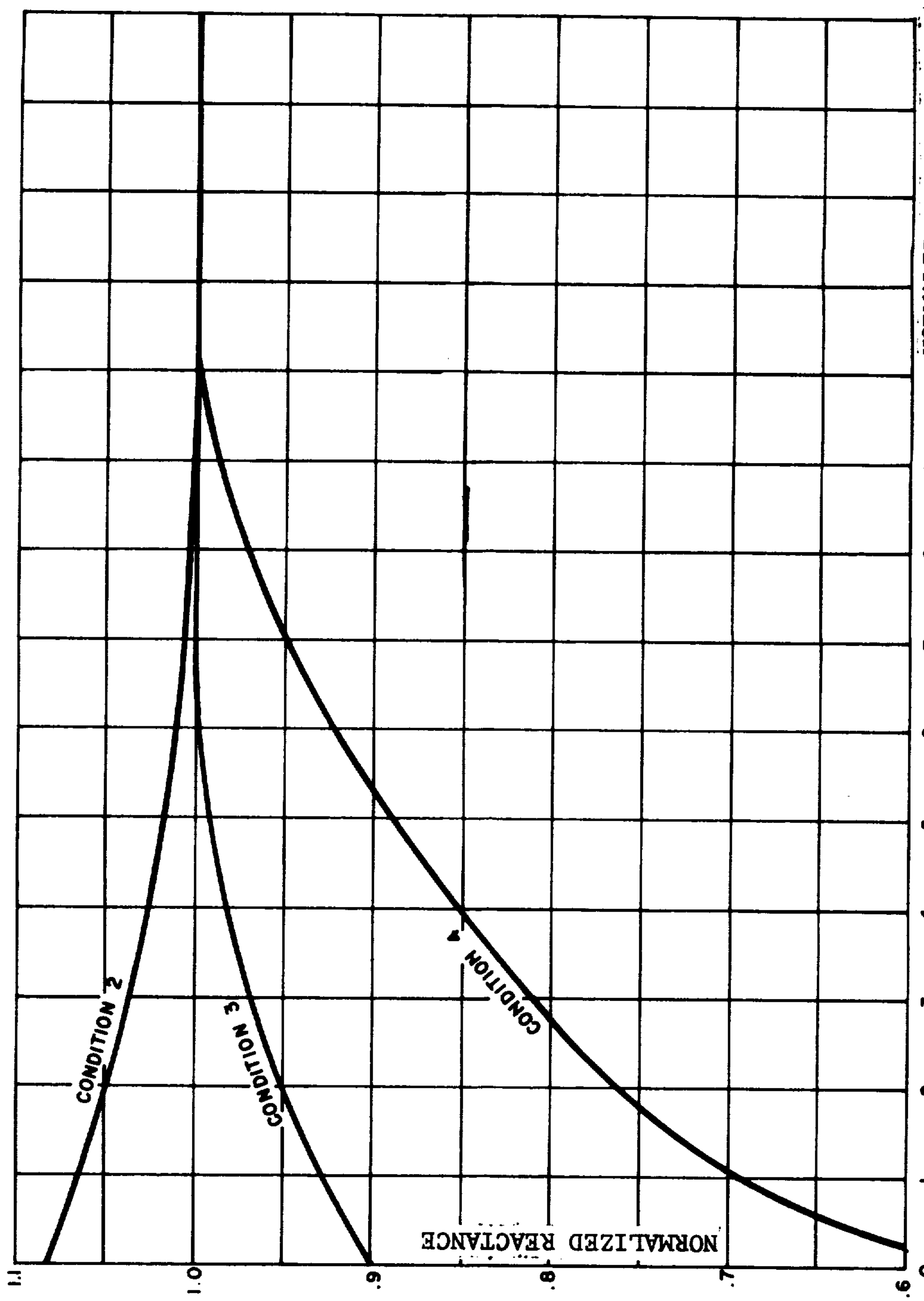


Figure A-1. Component Reactance as Function of Flux Density

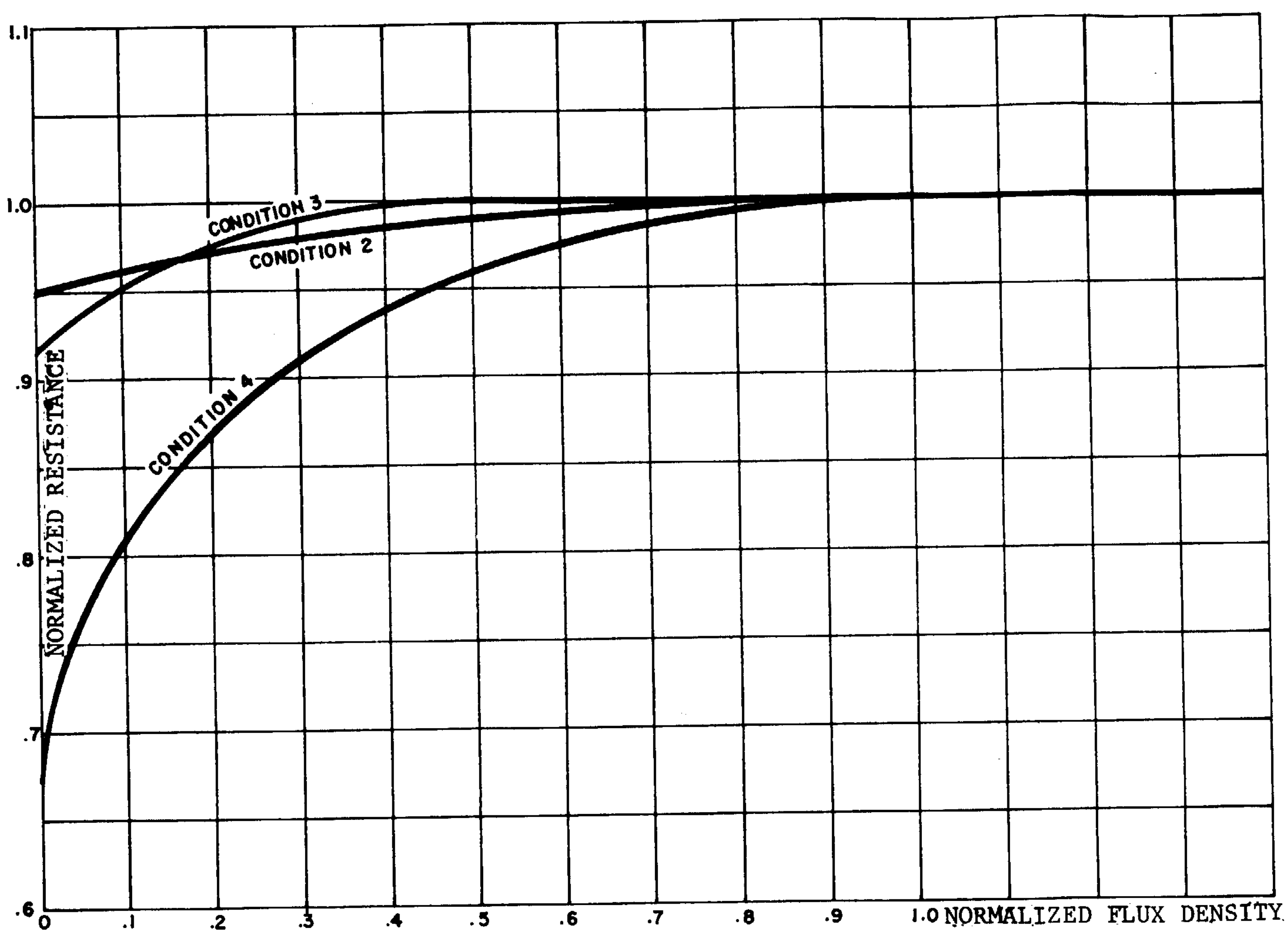


Figure A-2. Component Resistance as Function of Flux Density

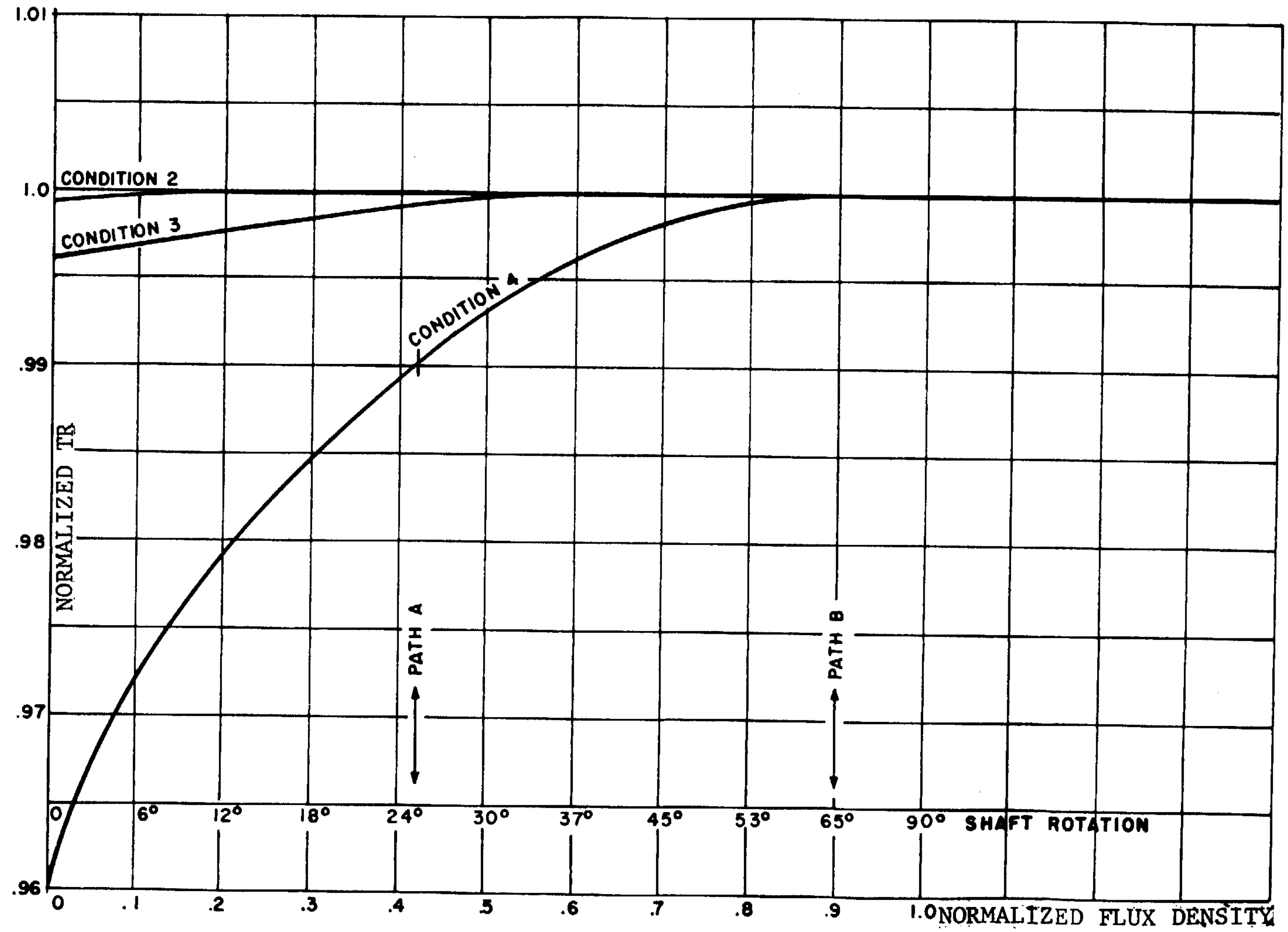


Figure A-3. Component Transformation Ratio as Function of Flux Density

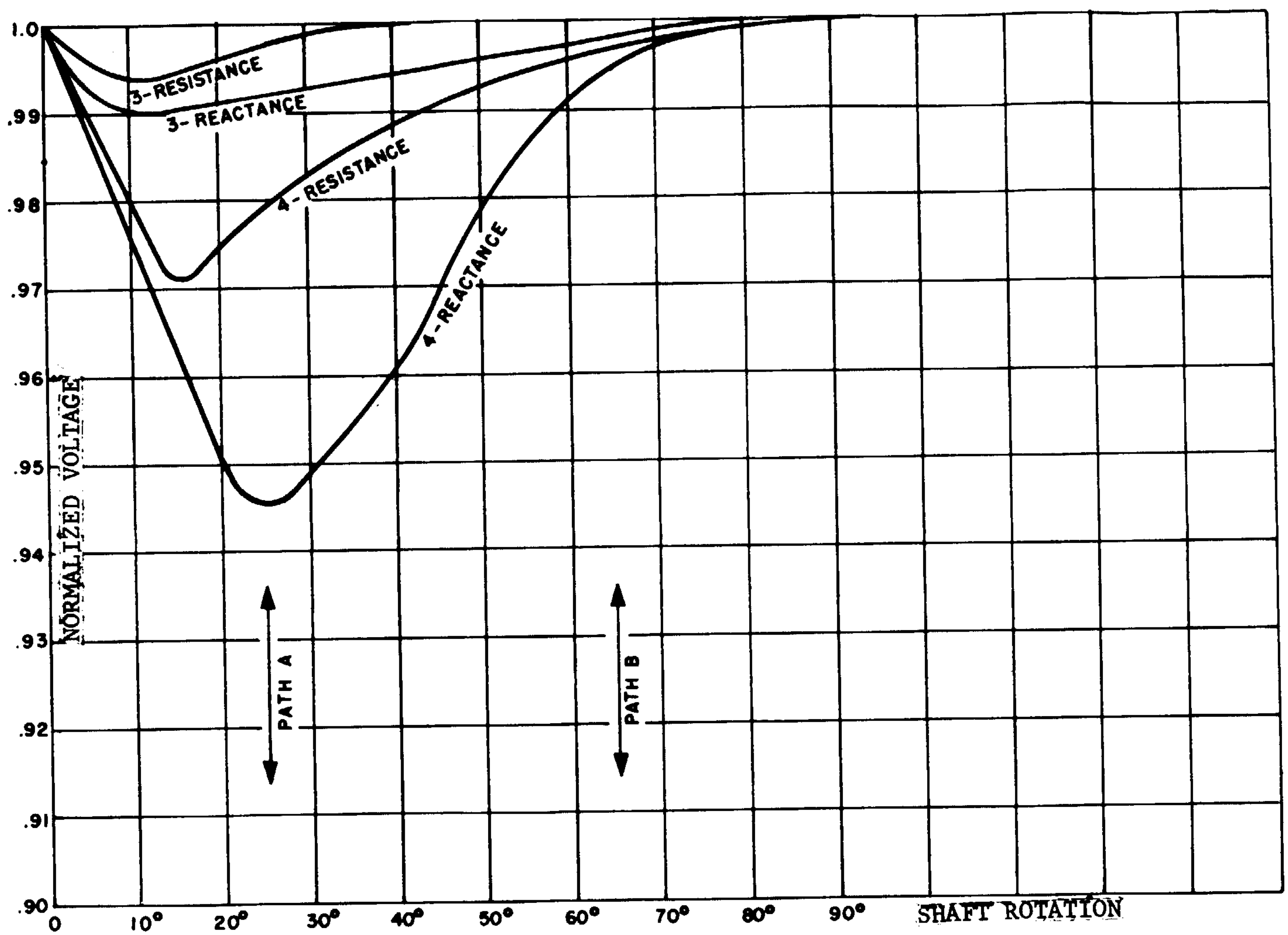


Figure A-4. Component Impedance as Function of Shaft Angle.

NASA-Langley, 1962